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Industrial wastewater treatment by on-site pilot static granular bed reactor (SGBR)

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Abstract

The on-site pilot-scale Static Granular Bed Reactor (SGBR) was used to treat the dairy processing wastewater at the Tulare Industrial Wastewater Treatment Plant (IWTP). A pilot unit with approximately 42.5 m^3 of active volume was operated for 7 months on a continuous basis with a range of 9 to 48 h HRT condition at ambient temperature. Throughout the whole study, COD and BOD_5 removal was consistently over 90% under a broad range of organic loading conditions ranging from 0.63 to 9.72 kg/m^3/d. TSS removal was also greater than 80% on average. In terms of organic removal, the SGBR system was robust to the temperature variations ranging from 10 to 29 °C. The adequate periodic backwashing consistently provided the maintenance of a head loss and the wastewater level in the reactor. Based on these results, the SGBR seems to be an excellent alternative for the required pretreatment system from the Tulare IWTP. Several benefits for IWTP could be provided by a full scale application of SGBR due to its simple design and operational advantages over conventional high rate anaerobic systems.

Key words: backwashing, dairy processing wastewater, high rate anaerobic process, pilot scale reactor, static granular bed reactor (SGBR)

INTRODUCTION

Treatment of dairy processing wastewater has become an important issue due to the growth of dairy industry as the demand for dairy products increased. Dairy processing effluents generated from cleaning of transport lines and equipment between production cycles can result in environmental problems in terms of high organic load on the local municipal sewage treatment systems (Eroglu *et al.* 1991; Perle *et al.* 1995; Danalewich *et al.* 1998). Dairy wastewaters are typically characterized by its high concentrations of organic matters resulting from protein, fat, and carbohydrate in forms of lactose. The waste also contains high levels of nitrogen and phosphorus as well as various cleaning and sanitizing agents, which results in a difficult waste for treatment systems (Brown & Pico. 1979; Perle *et al.* 1995; Omil *et al.* 2003).

The Industrial Wastewater Treatment Plant (IWTP) at the city of Tulare, California treats wastewater from dairy processing industries including cheese, ice-cream, and butter manufacturers. The current treatment plant includes preliminary screening and an anaerobic treatment process (bulk volume fermenter) followed by aerobic treatment in partially aerated/facultative lagoons. Due to tighter regulatory wastewater discharge controls and an increase in the discharge from industry, the City of Tulare is in the midst of expanding the IWTP to handle these additional flows and loads. The existing IWTP, with a capacity of 201,100 m^3/d, is being expanded to meet the new effluent quality criteria limits and increasing industrial wastewater discharge from the various manufacturers. Therefore, a more robust and cost-effective wastewater pretreatment system is required to treat the unique and high-strength wastewater.

Anaerobic treatment processes are preferred methods for treating dairy wastewater due to their advantages for treating industrial wastewaters with higher biodegradable organic matters and the characteristics of the dairy wastewater while aerobic treatment processes require high energy consumption for aeration and generate large amounts of sludge (Speece 1983; Gavala *et al.* 1996; Yan *et al.* 1989; Rajeshwari *et al.* 2000). Moreover, several high rate anaerobic systems such as the upflow anaerobic sludge blanket reactor (UASB) and the anaerobic filter (AF) were investigated to treat the dairy wastewater due to their high suitability compared to the conventional treatment process (Córdoba *et al.* 1984; Omil *et al.* 2003; Tawfik *et al.* 2007).

The static granular bed reactor (SGBR) is a simple, downflow high rate anaerobic system developed at Iowa State University and licensed by Envirotech System, Inc. (Lawton, IA). It utilizes a bed of active anaerobic granules in a downward flow regime. The performance of the SGBR has been demonstrated in numerous laboratory and pilot studies. The SGBR has been used to treat synthetic wastewater consisting of non-fat dry milk, municipal wastewater, pork slaughterhouse wastewater, and landfill leachate with excellent results (Mach & Ellis 2000; Roth & Ellis 2004; Debik *et al.* 2005; Evans & Ellis 2005; Park 2008). Moreover, the SGBR was also tested at low temperatures, between 8 and 15 °C, for municipal wastewater treatment (Evans 2004). Therefore, the SGBR appears to be an suitable option for this industrial wastewater based on the successful demonstration of SGBR treating a variety of wastewaters including high-strength packinghouse wastewaters (two sites), paper mill wastewater, and landfill leachate at ambient temperature (Roth & Ellis 2004; Debik *et al.* 2005; Aydinol *et al.* 2007; Park 2008).

In this study, an on-site pilot-scale SGBR was tested to evaluate its ability to treat the dairy processing wastewater and to determine its potential for full-scale application. Moreover, to develop the full-scale design parameters; e.g., hydraulic retention time (HRT), organic loading rate (OLR), and backwash criteria; the pilot reactor was evaluated at various operational conditions.

MATERIALS AND METHODS

Reactor set-up

A pilot-scale anaerobic reactor (SGBR), constructed of stainless steel, was installed on site at an industrial wastewater treatment plant in Tulare, California. The on-site pilot scale SGBR reactor consisted of a 62.3 m^3 reactor with 42.5 m^3 of working volume, a 70.8 m^3 tank for feed storage, a 8.6 m^3 tank for effluent storage, a 8.6 m^3 tank for backwashing discharge, a 1.4 m^3 tank for caustic soda, PVC pipes and fittings, several valves for sampling and operation control, progressing cavity pumps for feeding and backwashing, and a gas meter (Figure 1). The underdrain pipe was placed in the middle of the gravel bed in the bottom of the reactor to allow for effluent discharge and backwashing of the SGBR. Effluent was discharged by gravity through one of eight positions from 1.5 to 3.7 m to control the water level in the reactor. A semi-circular shaped pipe (weir) was installed above the operating water level in the reactor to allow separation and drainage of backwashed water from the granular bed.

The gas produced from the SGBR system was collected through the port on the top and vented using a 2.5 cm PVC piping. The biogas production rate during the system operation was measured using a gas meter after passing through a steel wool scrubber to remove hydrogen sulfide. The pressure and water level changes in the reactor were monitored using a manometer and a sight glass pipe located from 3.4 to 4 m from base.

The reactor was seeded with approximately 25.5 m^3 of anaerobic granules from City Brew Brewery in La Crosse, Wisconsin and started up on September 16, 2008. The reactor was fed with the

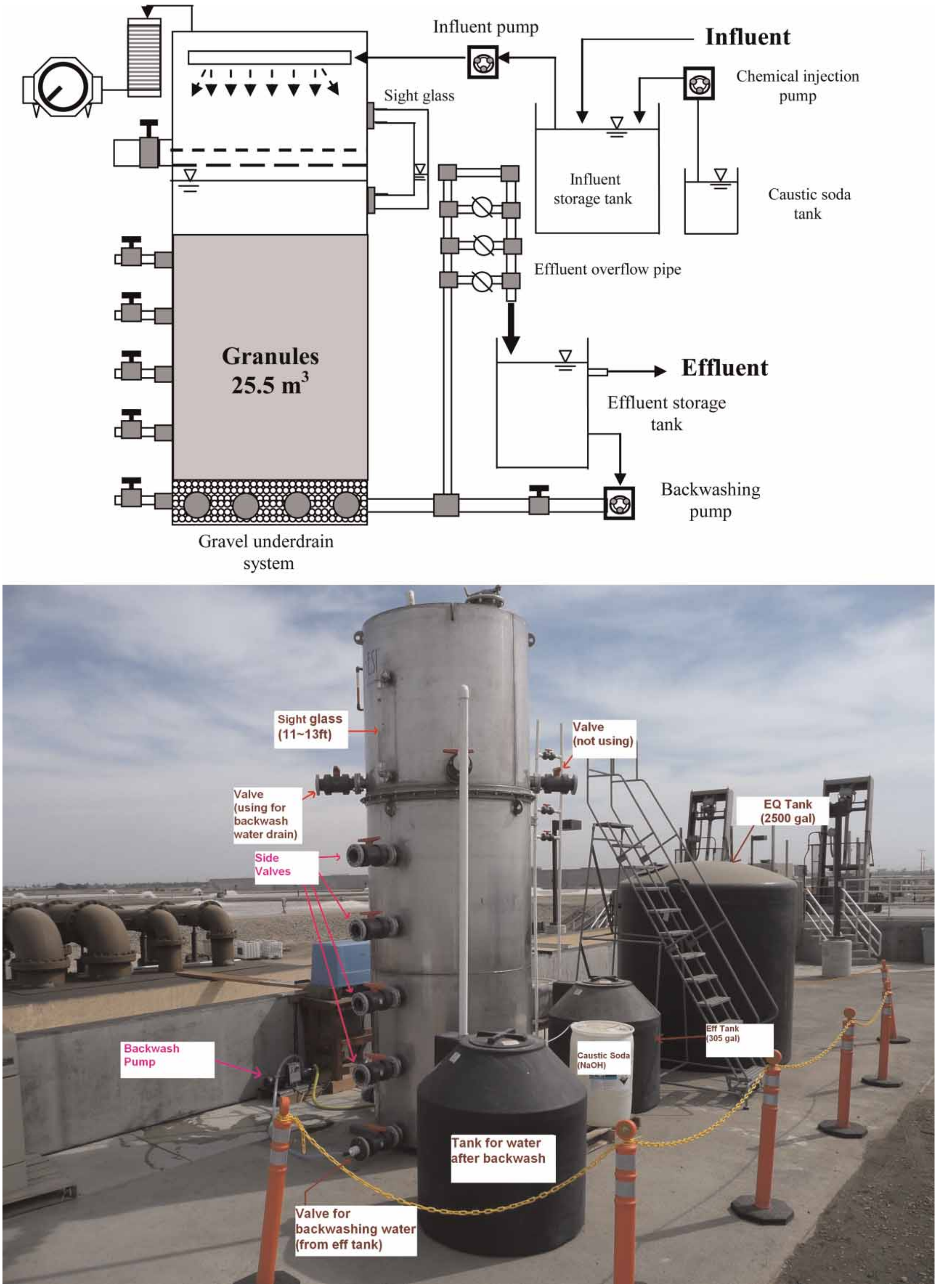

Figure 1 | Schematic of the pilot-scale SGBR system.

industrial wastewater pumped from the water stream before the screens of Tulare industrial wastewater plant. Treated effluent from the reactor was discharged to the influent through the treatment plant. The SGBR system was operated on a continuous basis with a 48 h HRT initially to maintain around 1.5 kg/m^3/d of OLR. The HRT and OLR were varied after start-up to demonstrate the performance characteristics of the SGBR system applied to this wastewater stream (Table 1). After

Table 1 | HRT and OLR schedule of SGBR

HRT (hours)	Operation time (days)	OLR ($kg/m^3/d$)
48	42	1.47
96	10	0.72
72	4	0.93
42	7	1.41
36	31	1.77
30	24	2.08
24	42	2.97
18	8	3.46
12	13	6.27
9	5	7.31

system showed its stability for a while at each operating condition, the HRT increased to evaluate the highest potential of this system treating dairy processing wastewater.

Analytical methods

A portion of the influent and effluent was sampled and analyzed 4–5 times a week to determine the performance of the reactor. For these analyses, effluent samples for chemical oxygen demand (COD), biochemical oxygen demand (BOD), volatile fatty acids (VFAs), total suspended solids (TSS), volatile suspended solids (VSS), and alkalinity were taken from the effluent tank and determined according to Standard Methods for the Examination of Water and Wastewater (APHA 1998). The COD and VFA tests were performed by the HACH method using HACH reagents and a HACH spectrophotometer. TSS and VSS measurements were performed by the filtration method (Standard Methods, section 2540 D and E) with glass fiber filter paper (Whatman GF/C, 1.2 μm pore size). Alkalinity was determined by titration method. Partial Alkalinity (PA) is the titration to an end point of pH 5.75 and the Intermediate Alkalinity (IA) is the titration from 5.75 to 4.3 (Ripley *et al.* 1986). The soluble COD was measured using the filtered wastewater sample to monitor the COD mass balance in the system. The influent and effluent wastewater pH and temperature were measured using an electronic pH meter. Biogas analysis was performed during the operating period. The gas samples were collected and analyzed with a Gow Mac gas chromatograph for gas composition. The biogas sample was also analyzed by BSK analytical laboratory in Fresno, CA. The specific methanogenic activity tests (SMA tests) were conducted at different HRTs to measure the activity of granules for the conversion of soluble substrates into methane. The SMA tests used in this study were a modification of the SMA test by Rinzema *et al.* (1988). Experiments were carried out in 250 mL serum bottles by batch tests. All tests were performed in duplicate at constant temperature (35 °C) and 160 rpm oscillations controlled in a shaker (Incubator Shaker Series 2, NewBrunswick Scientific Co., Inc.). The volume of biogas produced and the methane concentration in the headspace were measured at each time interval to determine the SMA. The granules were sampled from two sampling ports at different levels (0.6 and 1.2 m) to monitor the changes of activity of the granules as a function of height within the reactor.

RESULTS AND DISCUSSION

Organic removal

After the granules were placed in the reactor, the system was started at a 48 h HRT to maintain the start-up operating conditions which provided the necessary acclimation time for the biomass and

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system stability. The OLR at this time was approximately 1.5 kg/m^3/d, which was within the range of the recommended start-up loading rates compared to a previous SGBR study (Roth & Ellis 2004; Park 2008). After 9–14 days of operation, the SGBR showed stable operation, resulting in over 90% COD removal and over 80% TSS removal due to the rapid start-up of SGBR.

This study showed over 94% of COD and 89% of TSS removal efficiency by the pilot-scale SGBR during the operation as shown in Figure 2. The SGBR was operated at an average temperature of 19 °C, which can be classified as the operation under mesophilic and psychrophilic conditions throughout the study. No heating was provided to the SGBR as it is fully functional at ambient temperatures. Overall wastewater characteristics were shown in Table 2. The average influent COD, TSS and BOD_5 concentrations were 2,883, 493, and 1,637 mg/L, respectively. In terms of organic removal efficiency, the performance of the SGBR was not significantly affected by temperature variations between 10 and 29 °C. After the initial operation, COD removal efficiency was above 92% even during the period of system instability due to clogging from excessive debris in the influent. Moreover, after installation of the EQ basin, over 96% COD removal was obtained at an HRT as low as 12 h. TSS removal fluctuated from 70 to 88% during the start-up period. However, once the system stabilized, the average TSS removal remained greater than 90%. The influent was sampled from the main influent channel, and it was assumed that there was not a significant change in the COD or TSS through

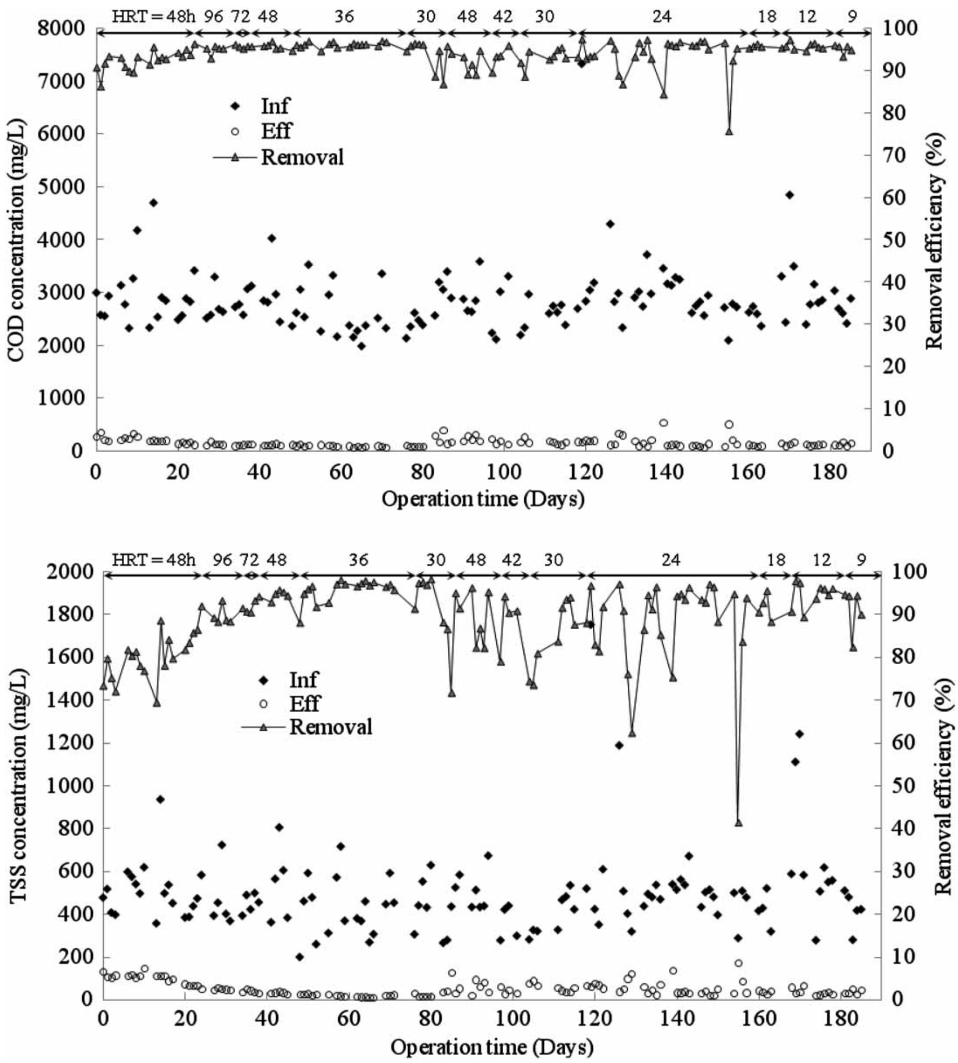

Figure 2 | Variation of COD and TSS concentrations with removal efficiency in pilot SGBR system (Day 0 corresponds to September 16, 2008).

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Table 2 | Characteristics of dairy processing wastewater

Parameter	Value
pH	5.79 ± 0.67
Alkalinity, mg/L as $CaCO_3$	726 ± 196
TSS, mg/L	493 ± 196
VSS, mg/L	486 ± 196
Total COD, mg/L	2,883 ± 631
Soluble COD, mg/L	1,629 ± 286
BOD_5, mg/L	1,637 ± 423
VFA, mg/L as HAc	34 ± 14

the EQ tank. This was verified by comparing the SGBR influent with the influent channel sample quality. These two sampling points had similar average COD and TSS concentrations ($p = 0.155$) during the test period.

During this study, the average BOD_5 concentration in the influent, the BOD_5 concentration in the effluent, and the NH_3-N concentration in the effluent were 1,630 mg BOD_5/L, 51 mg BOD_5/L, and 55.7 mg NH_3-N /L, respectively. Since the ammonia nitrogen concentration in the effluent was not high, there was no possibility for ammonia inhibition in the system. High BOD_5 removal efficiencies (96% on average) were achieved indicating a highly treatable wastewater with the SGBR.

pH, alkalinity and VFAs

The pH, alkalinity, and VFAs are important monitoring and control parameters for digester operation, especially considering the marginal performance of other anaerobic systems tested at Tulare. The optimal pH range for the methane production is between 6.5 and 8.2 (Speece 1996). The pH of the influent wastewater has fluctuated from 4.7 to 8.6 due to the variety of discharges containing caustic and acidic cleaning agents and other chemicals from the industries contributing to the plant, which required the pH control for the SGBR system. Sodium hydroxide (caustic soda) was used for pH adjustment. The effluent pH was stable with an average pH of 7.24. After Days 100, the caustic soda addition was reduced to save the operating costs, which decrease the effluent alkalinity from 873 to 516 mg/L as $CaCO_3$ in average. However, this effluent alkalinity decrease did not affect system stability.

The ratio of IA to PA (IA/PA) was monitored as an indicator of digester stability. The ratio of IA/PA between 0.1 and 0.35 is recommended for digester operation (Ripley *et al.* 1986), and for this study the ratio in the effluent was 0.25 on average (Figure 3). The effluent VFA was less than 35 mg/L as acetic acid throughout the study, which indicates there was no accumulation of fermentation intermediates, such as VFAs. This is an excellent indication that the anaerobic microorganisms were operating efficiently during the test conditions in this study. The ratio of VFA to alkalinity is used for indicating the process stability in the digester, which was monitored to ensure proper digestion conditions plant (Ripley *et al.* 1986). A well operated digester has the ratio of VFA/ALK less than 0.1–0.2, while the ratio of VFA/ALK between 0.3 and 0.5 indicates a potential for upset and possible need for corrective action. If the ratio is higher than 0.8, the digester becomes acidified and inhibition of methane production can occur. The ratio of VFA/ALK had a little increase after Day 100 due to the reduction of caustic soda addition in the influent storage tank. However, the ratio of VFA/ALK in the effluent varied from 0.02 to 0.12 during the all operation, which also indicates the excellent stability of this system and lack of inhibition of methanogens by VFA accumulation. A pH in the normal range

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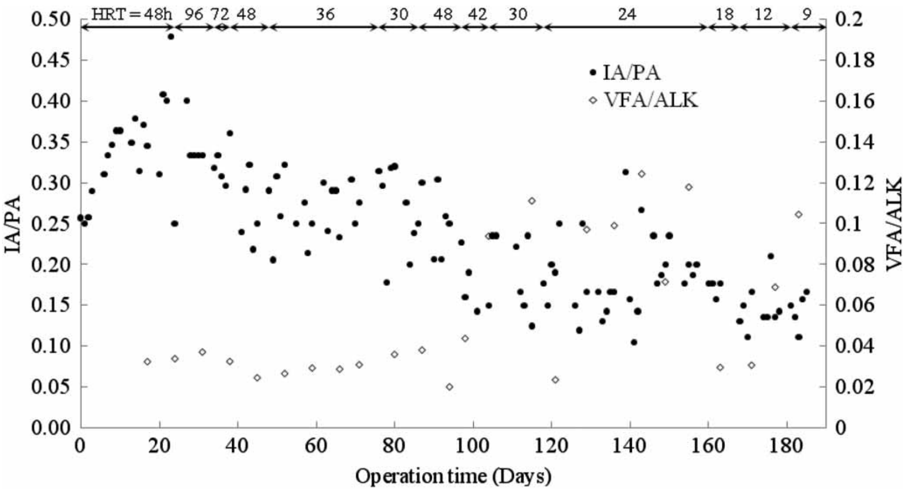

Figure 3 | Variation of IA/PA and VFA/ALK.

and low ratio of VFA/ALK suggested that the SGBR system was operating in an extremely stable condition.

Conductivity

The electrical conductivity (E.C.) of the waste was also monitored for the influent and effluent from the SGBR pilot unit using the City's meter in the lab. As mentioned above, caustic soda (sodium hydroxide) was used for pH control of the influent. Therefore, some rise in conductivity was included from this chemical addition prior to influent sampling so the results presented here are soley based on the anaerobic process. The influent E.C. ranged from 800 to 900 μS/m and the effluent ranged from 1,100 to1,300 μS/m. Over the last four months of the study, the E.C. increase through the SGBR averaged 374 μS/m.

Organic loading rates

During the start-up the average OLR was 1.47 kg/m^3/d. The OLR was gradually increased by stepwise decrease in HRT after a pseudo-steady state at each OLR was achieved. The influence of the OLR on the system process efficiency was evaluated under a broad range of organic loading conditions ranging from 0.63 to 9.72 kg/m^3/d and HRTs ranging from 96 to 9 h (Figure 4). COD and TSS removal efficiency were consistently above 90 and 80%, respectively. Occasional lower removals were experienced, but these were only brief occurrences that were not related to the biological health of the system, but rather the hydraulic capacity of the SGBR (e.g., when the granule bed became clogged, there was a need for additional backwashing that impacted the COD and TSS removal efficiencies slightly). Once the system was stable and an effective backwashing strategy was developed, the removal efficiencies remained high. As has been the case with other SGBR pilot studies, the SGBR performance was excellent over a broad range of organic and hydraulic loading rates, and the performance was not significantly affected by increases in the OLR up to 9.72 kg/m^3/d, the maximum OLR tested. This phenomena is indicative of the high biomass concentration retained in the SGBR which allows the food to microorganism ratio to remain low over a wide range of hydraulic and OLRs, resulting in a near constant and high organic and solids removal efficiency as evidenced by the results in Figure 4.

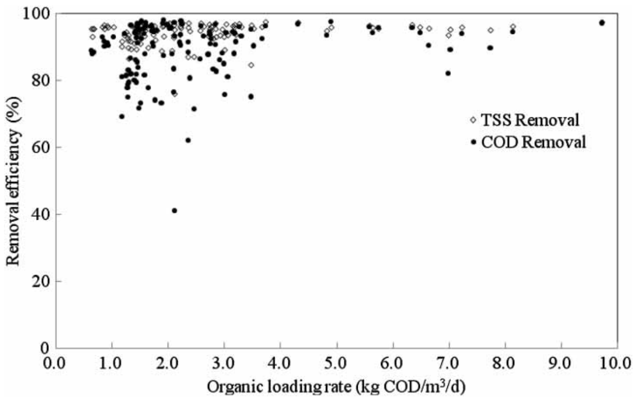

Figure 4 | COD and TSS removal efficiency at various OLRs.

Biogas production and composition

The biogas was collected through a PVC pipe installed at the top of the digester. The gas samples were collected in Tedlar™ bags through the valve installed on the pipe. The biogas was subsequently fed into the gas scrubber filled with a mixture of coarse and fine steel wool to remove hydrogen sulfide (H_2S). The gas treated by the scrubber was measured with a wet-test gas meter (RITTER® drum-type gas meter). Measurements of the volume of the biogas were converted to the volume at STP condition (0 °C, 1 atm). The production rate and the composition of the biogas produced by the SGBR are shown in Table 3. For the theoretical calculations, approximately 95% of the COD removal was assumed to go to biogas and the biogas was assumed to be 75% methane. The biogas production increased with the increase in the OLR (Table 3). However, a lower biogas yield than expected was observed throughout the study (Figure 5). A portion of this biogas inevitably escaped from the system during backwashing, since the system was depressurized during backwashing. In addition, a portion of the methane was leaving the system in the wastewater due to the solubility of methane. Methane solubility is affected by temperature, and Figure 6 shows a possible correlation between biogas yield and wastewater temperature. The biogas yield was varied from 0.1 to 0.3 m^3/kg COD and its average was around 0.2 m^3/kg COD. However, temperature variation from 10 to 25 °C did not affect the biogas yield seriously owing to the consistent treatability of this system at this temperature range. After Day 170, the biogas yield decreased to 0.1 m^3/kg COD, however, which seemed to correspond to the increase in the OLR.

Table 3 | Biogas production rate and composition

HRT (hours)	Production mean (L/day)	Composition CH_4 (%)	CO_2 (%)
72	1,481	73.1	17.4
48	1,680	–	–
42	1,887	–	–
36	2,139	80.4	16.2
30	1,895	74.3	11.6
24	3,794	65.1	26.8
18	3,754	67.6	23.9
12	4,382	65.3	23.3
9	4,588	–	–

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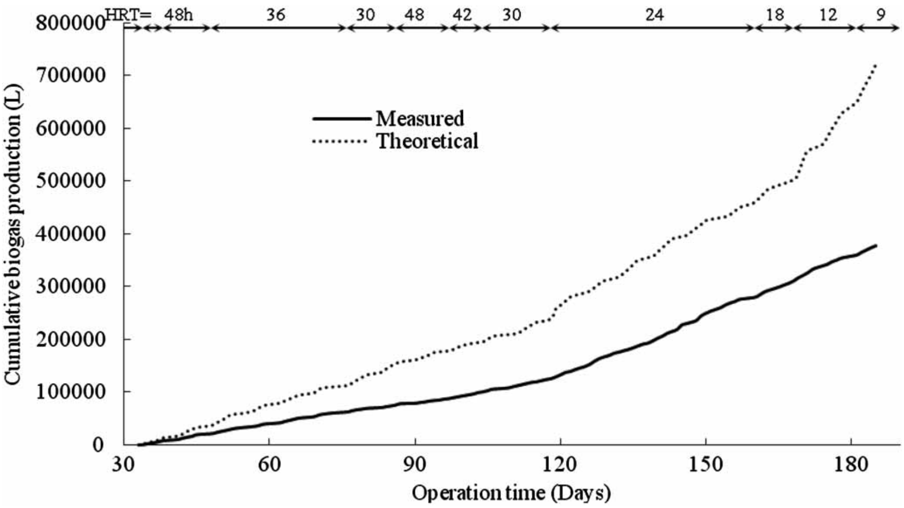

Figure 5 | Cumulative biogas production produced by the SGBR.

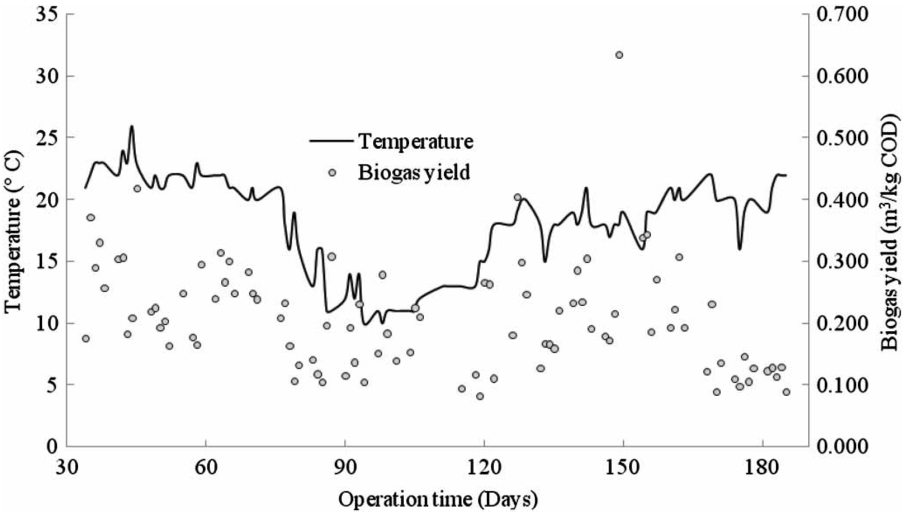

Figure 6 | Variation of biogas yield and temperature.

Specific methanogenic activity (SMA)

SMA tests were performed for the anaerobic granular sludge in the SGBR reactor to evaluate the methanogenic activity of granules throughout the study. SMA of the seed granular sludge was 0.333 g COD-CH_4/g VSS-d and activity measurements during the operation were varied from 0.270 to 0.478 g COD-CH_4/g VSS/d. Figure 7 shows the changes of activity of granule sampled from the middle (0.6 m) and bottom (1.2 m) of the bed at various OLRs. An increase SMA with increasing loading rates was observed between Day 86 and Day 125. This increase seemed to be affected by the supply of more sufficient organics from OLR increase as well as the effect of biomass acclimation to this wastewater due to stable operating condition maintained after Day 38. When OLR sharply increased from 4.9 to 9.7 kg/m^3/d, the biomass seemed to be affected by substrate inhibition owing to SMA decrease. However, the biomass maintained its activity with above 0.270 g COD-CH_4/g VSS/d of SMA and system did not show any break down such as VFAs rapid increase, decrease of methane production or rapid down of organic removal efficiencies.

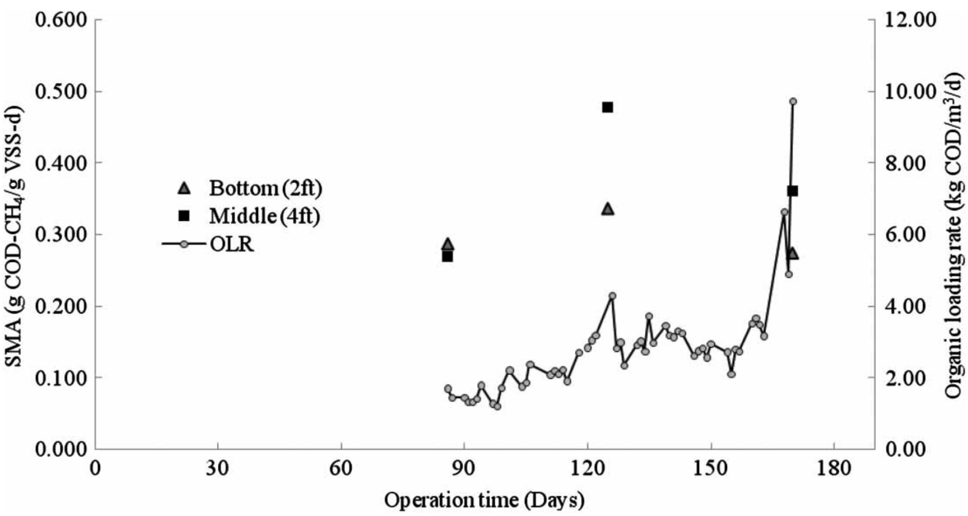

Figure 7 | SMA of granules from bottom and middle at various OLRs.

Backwashing

Periodic backwashing was performed once a week, or more often if necessary, to reduce headloss by removing the accumulated solids in the system. The 7–8.5 m^3 of effluent stored in the 8.5 m^3 effluent tank was pumped back into the underdrain at a flow rate of 0.3 m^3/min for 25–30 min. The spent backwash water was discharged into the main influent channel of the plant. The cumulative volume of treated wastewater and water used for backwashing were 924 m^3 and 43 m^3, respectively. The overall volume of water used for backwashing was 4.7% of the volume of treated wastewater.

During the initial period when headloss increases were experienced on several occasions, backwashing was conducted 2–3 times per week to alleviate the rapid water level increase in the reactor. After the EQ tank was placed in operation and much of the particulate debris was prevented from entering the reactor, a backwashing interval of once per week provided stable and sustainable system operation and maintenance. Following Day 93 of operation, the side valves at 0.6 and 1.2 m. were used in addition to the underdrain to introduce backwash water. This allowed better backwashing performance for the duration of the pilot study period. Backwashing was significantly reduced during the later periods of the study with no negative effects on the performance, and it is thought that a lower backwash rate could be used for the full-scale unit.

CONCLUSIONS

The consecutive 6 months operation of an on-site pilot scale SGBR showed the system stability due to the optimum range of VFA/ALK ratio in the effluent and consistent biogas production as well as over 90% of organic removal at various HRTs ranged from 9 to 48 h. This system achieved high organic removal efficiency under a broad range of organic loading conditions ranging from 0.63 to 9.72 kg/m^3/d. COD, BOD_5, and TSS removal were 94.2, 96.7 and 89%, respectively, on average. In terms of organic removal, the performance of the SGBR was not significantly affected by temperature variations between 10 and 29 °C. Moreover, the rapid start-up of the SGBR was achieved at an OLR of 1.47 kg/m^3/d, owing to the consistent treatability of the SGBR system within 9 to 14 days of start-up operation. The activity of anaerobic granular sludge (0.270–0.478 g COD-CH_4/g VSS-d as SMA) in the SGBR reactor was maintained during the study. The periodic backwashing strategy developed was effective for maintaining a stable head loss and wastewater level in the reactor after a process of trial and error.

Based on this pilot study, the Tulare wastewater appears to be an excellent candidate for pretreatment with the SGBR anaerobic process as the system was stable during all operating scenarios and did not exhibit toxicity or shock load problems that have plagued some of the other systems. A full-scale application of the SGBR system to treat this or similar wastewaters promises to provide exceptional benefits to the industrial and municipal community due to its simple design and operational advantages over conventional high rate anaerobic systems and its ability to handle higher organic and solids loads. In addition, the SGBR is able to provide high levels of treatment at ambient temperatures, eliminating the need for wastewater heating.

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